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MEASUREMENT OF $\bar{P}$ GRAVITATIONAL MASS

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A cooled $\bar{p}$ source will soon be available at Fermilab. As a high energy accelerator source it offers a unique advantage for realizing the highest center of mass collision energies. We may also ask (as many others have[1]) what unique non high energy applications such a source may have.

This note points out the particular systematic advantages counter circulating $\bar{p}$ & p beams in the same cooling ring have for determining a possible sign difference between the gravitational mass of the $\bar{p}$ & p. This is not to suggest that such a determination is clearly possible in such a configuration since, assuming opposite signs, the vertical separation of $\bar{p}$ and p beams from this effect alone is

$$\delta_{p/\bar{p}} \approx \frac{2m_p g}{m_p(\omega_\beta)^2} \approx 0.5 \times 10^{-10} \text{ cm} \qquad (1a)$$

in a machine such as the Fermilab electron cooling ring ($\omega_\beta/2\pi = 1$ MHz). If the 200 MeV p($\bar{p}$) in the ring were braked down to, say 2 MeV (which we shall see is possible, in a practical manner, via stochastic cooling) then the focusing is also diminished, giving,

$$\delta_{p/\bar{p}} \sim 10^{-8} \text{ cm.} \qquad (1b)$$

The merits of such a measurement must be considered relative to those of the Stanford "falling $e^{\pm}$" experiments:[2]

1. $M_p \simeq 2000\, M_e$. However notice that "mass" does not explicitely enter into Eq. 1. Nonetheless, in an optimized "real" experimental design one would try to take advantage of this intrinsic enhancement.

2. The "patch effect" was the scourge of the Stanford experiments. Grain boundaries in the surrounding vacuum pipe walls create random, small <u>electric</u> fields which are a dominant force on a <u>free</u> <u>falling</u> e^+/e^-. In a storage ring, with identical <u>average</u> p and $\bar{p}$ beam orbits the patch impulses will average to zero over the (very) long observation times which would be required to observe $\delta_{p/\bar{p}}$.

3. The Stanford experiment was <u>in</u> <u>principle</u> highly sensitive to systematic effects since it required separate <u>absolute</u> measurements of "free fall"for electrons and then positrons. A storage ring experiment would be a null type ($m_p = m_{\bar{p}}$). Systematic influences investigated so far (the most serious being 2. above) cancel or average to negligible levels over the measurement time.

4. On the other hand potentially (if gravity dominates) large signals are anticipated in a free fall experiment (i.e., 1 m = $\delta_{p/\bar{p}}$). A storage ring experiment would be <u>complimentary</u> to the free fall experiment. This comparison suggests that measuring $\delta_{p/\bar{p}}$ directly is <u>not</u> what we would like to do with counter circulating beams. Is there a signal observable which increments proportionally with time (as free fall)? If either the circulation frequency or betatron frequency were sensibly coupled to beam displacement,one could possibly devise a phase detector which would count out accumulating phase between $\bar{p}$ beam and

p beam Schottky signals.

An important effect unique to counter circulating beams is the beam-beam interaction. For low intensities (10^8 $\bar{p}$,which is the number per MR cycle anticipated in a final accumulator design) beam-beam attraction is less than the gravitational effect:

$$F_{\text{Beam-Beam}} = \frac{1}{4\pi\varepsilon_o} \cdot \frac{4N_e{}^2\delta}{C\ \ r^2} \simeq 10^{-26} \text{ Newtons} \qquad (2)$$

whereas

$$F_{\text{grav}} = 2m_p g \simeq 4 \times 10^{-26} \text{ Newtons}$$

For

$N = 10^8$ $\bar{p}/p$ in stored beam

$r = 1$ cm - beam radius

$C = 100$ m - machine circumference

$\delta = 10^{-6}$ cm

To imagine such minute beam displacements it must be assumed that the two beams are identical in both momentum and transverse structure. Being stored in the same lattice guarantees this if they initially are prepared identically. In fact, we have a powerful natural way to accomplish this: stochastic cooling. Unlike with electron cooling it is easily possible to simultaneously cool both p's and $\bar{p}$'s. The only new constraint is the pickup-kicker spacing,which must obviously be the same for particles leaving the pickup in either direction. Thus diametrically opposite pickup/kicker pairs are required.

Newly injected beams, of quite different origins, can be cooled to precisely identical forms in ~ few seconds (for 10^8 $\bar{p}/p$).[3] Since the same electronic channel handles both type particles, there can be no systematic error introduced. The same pickups used to transverse cool the beams can serve as displacement sensors for the experiment. Notice that doing this eliminates any zero offset signal due to imprecise geometrical alignment of pickups.

We may now ask, given an ideal situation as described above, how long it is necessary to observe (average) to resolve a displacement ~ 10^{-8} cm within an ~ 1 cm beam? Statistical fluctuations in beam displacement are ~ $\sigma_{Beam}/\sqrt{N_{obs}}$ where N_{obs} is number observed. We need $N_{obs} \sim 10^{16}$. Assuming good statistical mixing of the beam particles per revolution (necessary for optimal stochastic cooling) within segments equal to the pickup's effective length we need to average over ~ 10^8 revolutions with 10^8 particles in each beam. For ~ 10 μs revolution period (particles at 2 MeV kinetic) this requires ~ 1000 s. This result assumes noiseless detection preamplifiers but is probably reasonable since only one channel is required. The required vacuum would be a formidable problem for such slow particles.

References

[1] U. Gastald, A Possible New Experimental Approach to the Study of the $\bar{p}p$ System at Low Energies, CERN $p\bar{p}$ Note 13, October 10, 1977.

[2] W. M. Fairbank et al., in Experimental Gravitation, edited by B. Bortotti, (International School of Physics, Enrico Fermi, 1974).

[3] W. Kells, Stochastic Cooling, Fermi National Accelerator Laboratory Internal Report TM-827, October, 1978.